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Sediment and nutrient deposition in different riparian forests and floods of the Middle Paraná River

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Abstract

Sedimentation processes are important to the dynamics of lowland fluvial systems and depend on the characteristics of floods and of riparian ecosystems. The few known studies for the Paraná River system analyzed only summer floods without considering the context in which the sedimentation occurred. This study focuses on sedimentation in three riparian forests during one summer and two winter floods of the Paraná River, quantifying the amount of deposited sediments, determining their texture, and measuring the associated quantities of Total Phosphorous (TP) and Total Nitrogen (TN). This study takes into account the elevations, floristic attributes, and geomorphologic context of the three forests, as well as water and sediment transport during floods. Differences in the floods' water discharge, wash load, and duration determined differences in the total amounts of drained water and mobilized sediments. The amount of sediments ranged from 0 to 510 kg m^{-2} in the different floods and riparian forests studied. The texture was statistically different between the two winter floods, and between some riparian forests. The analysis of nutrients showed that 1 to 4919 kg ha^{-1} of TP and 4.2 to 1152 kg ha^{-1} of TN were deposited during the three floods in all forest types. Our results show that the amounts from winter floods can be as important as those from summer floods. These results provide insight not only into the importance of winter floods in the deposition processes, but also into the role of both types of floods as natural instruments of fertilization for floodplain-river ecosystems.

KEYWORDS: sedimentation; vegetation; phosphorous; nitrogen; floods; Paraná River.

INTRODUCTION

Sedimentation that occurs during floods is a key process of the dynamics of lowland fluvial systems. Sediments contribute to the construction of these systems themselves (e.g. through the formation of bars and islands and the lateral and vertical accretion processes), have an effect on different physical characteristics (e.g. water transparency), and carry essential macronutrients (e.g. phosphorous and nitrogen), thus contributing to the biogeochemical cycles of the floodplain-river ecosystems (Junk et al. 1989; Amsler et al. 2007).

Riparian ecosystems are widely recognized as sediment sinks (Lowrance et al. 1986). For instance, it was estimated that 90% of the sediment leaving agricultural fields in a coastal plain watershed in North Carolina remained in the wooded riparian zone (Cooper et al. 1987). Similar studies revealed that while 35 kg N ha^{-1} yr^{-1} entered the riparian zone, only <5 kg N ha^{-1} yr^{-1} left the watershed (Lowrance et al. 1984).

Since riparian forests border watercourses, they are among the first ecosystems receiving the main channel overflows, and their effectiveness in retaining sediments during floods has been already recorded in different rivers worldwide (Dezzeo et al. 2000; Steiger & Gurnell 2002). Most of the studies agree that although riparian forests are efficient in retaining sediments, their deposition is temporally and spatially variable. Sediment deposition depends on several factors, including vegetation type, geomorphological context, and flood characteristics.

The Paraná River in Argentina is considered as a mega-river (Latrubesse 2008), ranking second in South America after the Amazon River in terms of basin size and length. It is considered one of the 10 most important rivers in the world in terms of mean annual water discharge (Ashworth & Lewin 2012). The Paraná River is one of the three South American rivers that are responsible for 13% of all suspended sediment delivered to the oceans (Depetris & Paolini 1991).

The greatest volume of water and sediment enters the Paraná River during the rainy season of the austral summer (December-March), resulting in a flow regime characterized by the occurrence of summer floods every one to three years (Giacosa et al. 2000). However, the flow regime of the Paraná River varied substantially throughout the 20th century due to climate variability and anthropogenic disturbances (Rabuffetti et al. 2016). In contrast to historic patterns, autumn-winter floods have occurred annually for the last five years, and thus are becoming increasingly important to the fluvial system. As these autumn-winter floods present a lower liquid discharge than those that occur in the summer, their contribution to sediment and nutrient deposition has been recognized. In addition, deposition processes have not been quantitatively addressed for either the autumn-winter or the summer floods.

Studies related to sediment and nutrient deposition have been conducted for numerous rivers worldwide (Barrios et al. 1984; Mertes 1994; Tabacchi et al. 2000; Dezzeo et al. 2000; Steiger & Gurnell 2002). For the Paraná fluvial system, there are very few direct measurements of sedimentation resulting from summer floods. Some of these direct measurements indicate specific thickness of 0 and >1 m after the 2010 summer flood (Ramonell et al. 2011) and up to 1.40 m for the above normal 1982-1983 flood (Neiff et al. 1985). On the other hand, some modeling studies have estimated mean thickness of sedimentation of about 4 to 6 mm year^{-1} for the Middle Paraná River floodplain (Amsler et al. 2007), and other studies have estimated that the sediment deposited annually generates an average increase of floodplain bottom level ranging between 0.6 and 9.9 mm year^{-1} for the lower Paraná River floodplain (García et al. 2015). In addition to this scarcity of data, the relationships between deposition rates and vegetation types or geomorphology have not been considered, and the deposition caused by autumn-winter floods has not been measured at all.

In light of the recently reported changes in the flow regime of the Paraná River and, considering the crucial role of the deposited sediments in the dynamic of floodplain-river ecosystems, it is important to gain a better understanding of the amount of sediment and nutrient deposition during different types of floods of the Paraná River, taking into consideration the features of riparian forests and the geomorphological context in which sedimentation processes occur.

2. MATERIALS AND METHODS

2.1 STUDY SITES

The three study sites were located in natural levees and in a channel island of Las Arañas stream, a secondary channel of the Middle Paraná River, in the proximities of Diamante city (Entre Ríos, Fig. 1). The river's mean annual water discharge is ~17,000 $m^3 s^{-1}$ at the Paraná city gauge station, with extremes ranging from 8,000 to 60,000 $m^3 s^{-1}$ in the 100 years of records. Overflows usually take place when the main channel flow exceeds 20,000 $m^3 s^{-1}$ (Ceirano et al. 2000).

The main channel of the Paraná fluvial system transports 135 million tons $year^{-1}$of sediment (Amsler et al. 2007). Approximately 80% of the sediments are silts and clays, which travel as wash load; the remaining 20% consists of sands, which travel either as suspended sediment (medium and fine sands), or as bed load (very coarse to medium sands). Along its almost 700 km path, the Middle Paraná River has shaped a large floodplain described as a wetland macrosystem with high biodiversity and complex dynamics (Neiff et al. 2014). Generally, the topography is flat, with a longitudinal slope of around 0.1‰ or lower. Its soils are Entisols (Soil Survey Staff 1999), with Fluvents in the natural levees and Aquents in the lowest topographical zones (Orellana & Bertoldi de Pomar 1969). The climate is humid-subtropical, with a mean annual temperature of 19°C, and 900 to 1000 mm annual rainfall, 73% of which is recorded between October and April (Rojas & Saluso 1987).

In the study sites, the vegetation consists mostly of pioneer and riparian forests dominated by Willow (*Salix humboldtiana* Willd.) and River alder (*Tessaria integrifolia* Ruiz & Pav. var. *integrifolia*), which grow in sand bars and levees next to the main channel. We studied three types of forests: willow, willow-alder, and alder. Other communities along the Paraná River floodplain include gallery forests (*Albizia inundata* (Mart.) Barneby & J.W.Grimes, *Nectandra angustifolia* (Schrad.) Nees & Mart., *Inga uraguensis* Hook. & Arn., *Croton urucurana* Baill., *Erythrina crista-galli* L. var. *crista-galli*), herbaceous communities such as tall grasslands (dominated mainly by *Coleataenia prionitis* Nees), different types of marsh communities (dominated by *Polygonum* spp., *Ludwigia peploides* (Kunth) P.H. Raven ssp. *peploides, Echinochloa* spp., *Paspalum* spp. and *Panicum* spp.), and floating aquatic vegetation *(Azolla filiculoides* Lam., *Salvinia biloba* Raddi, *Eichhornia crassipes* (Mart.) Solms and *E. azurea* (Kunth) Solms) (Marchetti et al. 2013).

2.2 SEDIMENT TRAPS

In the three study sites identified, we assessed three different floods: the autumn-winter floods of 2014 and 2015, and the summer flood of 2016. Before these floods, we installed six sediment traps in each riparian forest studied – three in one location and three in another-. Sediment traps consisted of plastic squares of 0.30 x 0.30 m attached to the ground by stakes. Traps were georeferenced, and the closest trees were marked in order to find the traps after the floods occurred. Since we measured the elevation of sites where sediment traps were installed, we monitored the hydrometric level elevation and went to the field to recover traps as soon as the hydrometric level was lower than the elevation of sediment traps. There were no rain events before traps were recovered that could have produce sediment losses. Therefore, after each flood, the thickness of the sediments deposited was measured for a total of three records each trap, and a smaller sample of sediment was collected in each trap in order to avoid the edge effect. These sediment samples were dried to 106˚C to achieve constant weight. Sand, silt, and clay fractions were determined by the Bouyoucos (1962) hydrometer method. Total nitrogen was determined by the Kjeldahl method (IRAM 29572), and total phosphorus by the Bray Kurtz 1 method (IRAM 29570), prior to calcination to 600ºC and dissolution in hydrochloric acid 6 N.

2.3 FLOOD CHARACTERIZATION

Different data sources were used to characterize the three flood events studied. Daily water levels of the Paraná River were obtained from the Meteorological Information Center database (FICH-UNL) for the Paraná gauge station, and from the Direction of Waterways for the Diamante gauge station. An overflow level of four meters was considered representative of the study area (Ramonell et al. 2000) when analyzing flood duration. The total discharge from each flood event was calculated from the mean daily discharge reported for the Subfluvial Tunnel and Colastiné Sections by the Secretariat of Water Resources in Argentina. During the 2014 (winter) and 2016 (summer) floods, the wash load was sampled weekly at the Colastiné Section and processed at the Laboratory of Sedimentology (FICH-UNL). Quantities of dissolved solids and fine (silt plus clay) fractions were obtained from these water samples. Because we did not have a boat available to sampled weekly at the Colastiné Section its wash load for the 2015 flood could not be measured.

2.4 FOREST CHARACTERIZATION

Riparian forests were named according to the dominant species identified during the forest characterization process – i.e., willow, willow-alder, and alder. Before the 2014 flood, we analyzed one plot per forest – which included the locations of the six sediment traps - to determine elevations and characterize structural and floristic attributes.

Vegetation attributes were recorded according to methods classically used for vegetation studies (Mueller-Dumbois & Ellenberg 1974). The surface area of each plot varied according to the tree density – i.e., 400 m^2 in the more open forests (willow and alder-willow) and 250 m^2 in the densest one (alder). Inside each plot, tree density and diameter at breast height (DBH =1.3 m above the ground) were recorded by species, the percentage of soil coverage by shrubs was visually estimated, and the herbaceous coverage was measured by cutting six biomass squares of 0.20 x 0.20 m each. Biomass samples were dried to 106˚C to achieve constant weight.

Plot elevation was characterized by measuring 10 points in each site with geometric levelling (Fig. 2, Zrinjski et al. 2018). For reference, we used the water surface level of the Las Arañas stream, which even at its lowest level remains connected to the Paraná. This reference was calculated as the sum of the hydrometric level of the river on the day of sampling (measured at the gauge station of Diamante City) and an increase in the hydraulic slope of 4 cm km^{-1} (Gaudín & Vionnet 1999).

Resistance of vegetation to flow was obtained by considering tree density and diameter as a function of flow depth according to the following equation (Arcement Jr & Schneider, 1989):

$$Veg\ d = h \sum ni\ di / hwl$$

where:

$\Sigma\ ni\ di$ =the summation of number of trees multiplied by tree diameter, in meters

h =height of water on flood plain, in meters

w =width of sample area, in meters

l =length of sample area, in meters

The former procedure considers data collected at field and it is proposed as an alternative to use of the tabulate values for determining Manning`roughness coeficient for flood plains (Arcement Jr & Schneider, 1989). Since we don't have other neccesary variables we don't calculate Manning`coefficient, we just refer to vegetation resistance.

The geomorphologic context of each riparian forest was recorded in order to consider it during the analysis and interpretations of results.

2.5 STATISTICAL ANALYSIS

For all variables, homoscedasticity and normality assumptions were checked using Bartlett and Shapiro tests, respectively. A non-parametric Kruskal-Wallis test (and its posthoc contrasts) was applied to variables that did not meet the assumptions in order to check statistical differences among forests (DBH, elevation), and among forest and years (sediment weight). A one-way ANOVA was used to check statistical differences among forests for variables that meet the assumptions (dry biomass).

Textural differences in the deposited sediments from the floods and in riparian forests were analyzed. For this assessment, distance matrices were constructed from the distance index of Bray-Curtis (recommended for quantitative data, McCune & Grace 2002) and subjected to 4,999 permutations. These distance matrices were used to develop a sampling method, which delineated groups of sediments for the comparison. The differences between the groups were measuring using an MRPP (Multi-response Permutation Procedure). The

MRPP is a nonparametric procedure designed to test the null hypothesis of "no difference between groups of entities" (McCune & Grace 2002).

The level of significance for all statistical tests was α=0.05. The tests were performed in R language (R core team 2017) using R Studio (with packages such as Car, PMCMR) and Pc-Ord (McCune & Medford 2011).

3. RESULTS

3.1 FLOOD CHARACTERIZATION

The three studied flood events – autumn-winter 2014 and 2015, and summer 2016 - exhibited some important differences in the extent of liquid and solid discharges (Table I). The winter floods showed a greater similarity to each other than to the summer flood in terms of mean discharge; however, compared to the 2015 winter flood, the 2014 winter flood was more than two times in duration, and its highest water level was 0.80 cm higher (Fig. 3). Although the mean discharge of the two floods was quite similar, the 2014 flood was double the total drained water volume. In contrast, the duration of the 2016 summer flood was more than three times and more than seven times longer than the 2014 and 2015 winter floods, respectively. The water level of the summer flood was also between one and two meters above the water level reached in 2014 and 2015 winter floods; as a result, the drained water volume was four times higher in the 2016 summer flood than in the largest winter flood.

Wash load was different between the winter (2014) and the summer (2016) floods (Fig.4). Although their maximum and minimum wash load concentrations were similar (Table I), because of the substantial differences in their drained water volume the sediment mobilization in 2016 summer flood was substantially higher than that for the 2014 winter flood.

3.2 CHARACTERISTICS OF RIPARIAN FORESTS

3.2.1 STRUCTURE AND FLORISTIC COMPOSITION

The three riparian forests we studied showed variations in floristic composition and structure, as expected (Table II). Although the percentage of woody and herbaceous species was similar among the three forests, the total number of species, as well as the dominant species and the structural characteristics, differed. The greatest number of species was recorded in willow forest (48), while alder-willow and alder forests presented almost the same number of total species (34 and 32, respectively). In the arboreal stratum, tree density increased sharply from willow (2575 tress ha^{-1}) to alder-willow (4550 tress ha^{-1}), and to alder (7957 tress ha^{-1}) forests (Table II). On the other hand, diameter at breast height (DBH) decreased in the same order (from 21 to 13.8 to 5.3 cm, respectively) and the differences between each were statistically significant (p=0.000, Fig. 5). Both parameters (tree density and DBH), mainly, determined differences in the resistance of forests to flow (Table II): the alder forest presented more resistance (0.039) while the alder-willow offered the lowest resistance to flow (0.063). The shrubby stratum was better represented in alder (75% soil coverage) than in willow (30% soil coverage) forest; there was no shrubby stratum in the alder-willow forest. The herbaceous stratum (referred as dry biomass) was significantly different (p=0.003) between willow (2181 KgMS ha^{-1}) and alder (796 KgMS ha^{-1}) forest. In contrast, alder-willow forest was not statistically different from the other two forests (Fig. 5).

In terms of density and DBH, willow and alder forests can be considered as the oldest and the youngest forests, respectively, with the alder-willow forest of intermediate age. Dominant species also change according to forest age: alder (*Tessaria integrifolia*) was clearly dominant in the youngest and the intermediate age forests, while willow (*Salix humboldtiana*) dominated only in the oldest forest.

3.2.2 ELEVATION AND FLOOD DURATION IN THE THREE TYPES OF FORESTS

The elevation of landforms colonized by riparian forests was significantly different between willow and alder-willow forests (p=0.004), and between alder-willow and alder (p=0.014) forests (Fig. 6A). Non-significant differences were found between the oldest (willow) and the youngest (alder) forests. These differences in elevation resulted in different flooding duration in the riparian forests. Thus, while willow forest was flooded for less than one month and for slightly more than two months during the shortest and longest floods, alder-willow forest was flooded for one and almost three months in the same flood events (Fig. 6B). However, willow and alder forests were flooded for a similar duration (Fig. 6B´).

3.2.3 SEDIMENT AND NUTRIENT DEPOSITION

The amount of sediment deposited varied among the floods and the riparian forests analyzed (Fig. 7). The lowest and highest amounts of sediments were always recorded in willow (0 to 68 kg m^{-2} and 0 to 30 cm high) and alder forests (2 to 510 kg m^{-2} and 2 to 60 cm high) during all floods studied. In the willow forest, the amount of sediment was similar for the winter 2014 and the summer 2016 floods; however, for the same flood events the sedimentation was two times higher in the alder forest, and three times higher in the alder-willow forest, than in the willow one.

The texture of the deposited sediments was mostly silt-loam (Table III). Nevertheless, a higher fraction of sand was deposited in alder-willow and alder forests during the two most important floods (2014 and 2016), changing the sediment texture from silt-loam to loam. In contrast, an increase in the clay fraction during the 2016 flood changed the willow forest sediments from silt-loam to silty clay-loam (Table III). These changes resulted in statistically significant differences between the 2014 and the 2015 floods (p=0.024), between willow and alder-willow forests (p=0.0001), and between willow and alder forests (p=0.0000). Regarding nutrients, 1 to 4919 kg ha^{-1} of TP, and 4.2- to 1152 kg ha^{-1} of TN were deposited during the three floods in all forests. The deposition of both TP and TN did not vary much between the two winter floods (2014-2015), even when comparing the different forests. On the other hand, during the summer flood (2016), quantities of both nutrients were markedly higher and varied substantially among the three forests. either as bed materials (mainly sands) or as suspension materials (mainly silts and clays). The Paraná River moves 135 x 10^{6} tons year^{-1} of sediment, which are mostly supplied by the river's Andean tributary, the Bermejo River (Amsler & Prendes 2000). The largest sediment yield occurs from December to February when storms result in significant flows with sediment concentrations sometimes higher than 100 g l^{-1} (Amsler et al. 2007).

Thus, a heavy sediment load enters the Paraná River during the rainy season, sharply increasing its wash load concentration. According to the seasonality of these sediments, the highest wash load concentration is expected to be associated with summer floods. However, as the overall concentration is influenced by the levels of water discharge coming from the upper Paraná and the Paraguay Rivers – which, as Amsler et al. (2007) showed carry water with lower wash load concentrations - the wash load concentration of the summer floods can be strongly diluted at the middle and lower reaches of the Paraná River.

Our results show precisely this situation: while the winter 2014 flood (which is representative of the last five floods in terms of discharge and timing) was almost three times lower in terms of liquid discharge than the summer 2016 flood (137,143 and 484,622 Hm^{3} of drained water volume, respectively), the two were very similar in terms of solid discharge (47 to 103 and 11 to 118 m gl^{-1} as minimum and maximum wash load, respectively). The 2014 winter flood mobilized 9,720,529 Tn of wash load in 73 days, while summer 2016 flood mobilized 20,648,698 Tn in 233 days. In other words, the winter and summer floods transported 133 and 89 Tn of wash load per day, respectively. This illustrates that, although

2016 flood was more important in terms of duration, maximum hydrometric level, and drained water volume, the 2014 winter flood was more important in terms of wash load mobilization.

Because of their relatively low water discharge and duration, the importance of winter-autumn floods in sediment distribution is usually underestimated. However, considering their increasing occurrence in the last five years, our results suggest that winter floods will prove to be important not only as a means of annual water supply to the floodplain, but also in terms of sediment inputs.

4.2 SEDIMENTATION IN RIPARIAN FOREST

Final sedimentation depends not only on sediment inputs, but also on the roughness of ecosystems through which they have to move. Sediment and associated nutrients will be deposited according to vegetation characteristics and local topography, two of the main factors contributing to the “roughness” of a terrain (Dezzeo et al. 2000).

The three riparian forests studied here differed in floristic and structural features, in elevation, in the resulting flow resistance, and in the general geomorphological context as was summarized and integrated in Figure 8. Willow forest was topographically similar to alder forest, but sedimentation in the alder forest was three to five times higher than in the willow forest during the three flood events studied. Although we have considered just one replicate of each type of forest, differences in the amount of deposited sediment can be explained by tree density and shrub percentage, which are markedly higher in alder forest.

In a similar study, rapid and efficient sedimentation was associated with “intricate” tree vegetation on an island in the Orinoco River, in contrast to other places along the river, such as agricultural lands (Dezzeo et al. 2000). On the Garonne River, sites with natural riparian vegetation experienced higher sedimentation than poplar plantations in the floodplain

(Steiger & Gurnell 2002), suggesting that natural riparian vegetation promotes higher amounts of sedimentation than that occurring in riparian areas under anthropogenic management.

Our assessment of elevation showed that alder-willow and alder forests were statistically different topographically, with the former being the lowest. However, it was on the higher one, the alder forest, where the greatest amount of sediment was recorded during the three flood events. A filtering effect in which both direct interference of vegetal biomass and loss of velocity followed by passive sedimentation - usually called the “comb effect” (Prat et al. 1998) - has been proposed as the cause of increasing in sedimentation. Thus, in the alder forest, the higher density of trees determining the highest roughness value which combined with higher percentage of shrubs could have created “comb effect,” resulting in this forest exhibiting the highest sedimentation rate of the three studied.

Tree density and diameter as well as the depth flow (obtained from elevation) are considered to estimate the roughness imposed by vegetation in densely vegetated floodplains (Arcement Jr & Schneider, 1989). The results obtained here from considering tree density and diameter, and depth flow in the three studied forests showed that alder forest present the highest values (0.039 $m^2\ m^{-3}$, Fig. 8) representing a higher resistance to flow favoring the highest sedimentation recorded in this forest. On the contrary, the flow resistance of the willow forest was higher (0.054 $m^2\ m^{-3}$) than of the alder-willow forest (0.063 $m^2\ m^{-3}$), but the amounts of the deposited sediments were higher in the alder willow forest. This could be explained by elevation and amount of flooded days (Fig. 6B) since alder-willow forest was the lowest and consequently it remained flooded for more time.

In addition, the geomorphological features of the riparian zone have been identified as constraints to the contemporary patterns of flow hydraulics and sediment transfer within these zones (Tabacchi et al. 2000). Forests studied here have different geomorphological features.

Willow and alder-willow forests are located in natural lateral levees, while the alder forest is located on a channel island, in the sediment pathway itself. Even though alder forest had the lowest herbaceous cover and it was the second highest its location in the middle of the sediment pathway explains why it had the highest amount of sediment recorded during the three flood events.

The geomorphological context of the three forests studied could have influenced not only the amount of deposited sediments but also the sediments' texture. Willow and alder-willow forests are located in natural lateral levees, while alder forest grows in the path of the flowing sediment on a channel island. The texture of sediment deposited in these forests was markedly different: alder forests (as high as willow forests but located in the middle of the sediment pathway) always presented the highest proportion of sand, followed by alder-willow forest (topographically the lowest), and willow forest. The proportions of silt and clay did not seem to follow any pattern among forests and floods, although silt was always the better represented fraction.

Overall, the extent and type of sedimentation that occur in riparian areas of a lowland river system are determined by a variety of factors—i.e., sediment supply, vegetation of the riparian areas, elevation, and geomorphological forms and processes – and, just as important, the way that those factors interact.

As a result, sedimentation in tropical floodplains is highly variable both in time and space (Dezzeo et al. 2000). Our results showed amounts of deposited sediments were quite different, ranging from 351 to 2519 t ha-^{1} (or 35.1-251.9 kg m^{-2}) for the 2014 flood, and 0 to 165 t ha^{-1} (or 0-16.5 kg m^{-2}) for the 2015 flood, to 280 to 5097 t ha^{-1} (or 2.80-509.7 kg m^{-2}) for the 2016 flood. This results concur with those of similar studies: for the Orinoco River, Barrios et al. (1994) reported as much as 834 t ha^{-1} and Dezzeo et al. (2000) reported 736 t ha^{-}

^{1}; in the Garonne River floodplain, Steiger & Gurnell (2002) recorded 1 to 1601 t ha^{-1} for different sites and floods.

Regard to the Middle Parana River there are no similar data to compare our results, however thicknesses of sedimentation were reported by Ramonell et al (2011) after the 2010 summer flood for sites located 120 km north to our study area. Close to the main channel authors recorded 0, 1, 3, 5, 30 and more than 100 cm of sedimentation. After the 2016 summer flood, sedimentation in our study sites ranged from 3-13 cm in willow forest, from 22-49 cm in alder-willow forest and from alder 37-60 cm in alder forest.

The deposited thickness is a useful parameter to evaluate sedimentation, however it decreases with time due to the compaction processes. For this reason, deposited thicknesses have to be carefully used when data from different sites are compared. Despite this, sedimentation recorded in our study area varied within the range reported for other sites of the Parana river floodplain.

4.3 NUTRIENT DEPOSITION

Sediments deposited during floods are an important source of nutrients; among them, phosphorus (P) and nitrogen (N) are especially important for natural or implanted vegetation, algae production, and different biogeochemical cycles, among others (Junk et al. 1989; Daniels 1996; Boschetti et al. 2004). Between 1-4919 kg ha^{-1} (or 280 and 3370 mg kg^{-1}, to make comparisons easier) of Total Phosphorous (TP) were deposited in different floods and forests we studied. These TP amounts are considerably higher than those found in upland soils close to the study area, where between 200 and 300 mg kg^{-1} have been reported (Boschetti et al. 2000). Similarly, in the same riparian forests up to 22.5 ppm of Assimilable Phosphorus (AP) were deposited by the 2016 floods (unpublished data), which is similar to the 37 ppm of AP reported for the best soils in the nearby uplands of the Entre Rios province

(Di Nucci de Bedendo 2018). If P is not provided by the parental material, upland soils are usually poor in this macronutrient and it has to be added as chemical fertilizer to improve vegetal production (Boschetti et al. 2004). This highlights the importance of Paraná floods as a natural source of fertilization for surrounding grasslands and other ecosystems.

During the three floods studied, 4.2 to 1152 kg ha^{-1} of Total Nitrogen (TN) was deposited in the three forests. This range is markedly different from, but as variable as, the 21 to 272 kg ha^{-1} reported for the lower Orinoco by Dezzeo et al. (2000); in their study N concentration did not appear to be affected by texture or mineral abundance of the sediment deposited.

In the good upland soils of the Entre Ríos province, TN levels ranged from 0.20% to 0.29% (Boschetti et al. 2000), but levels up to 0.21% were recorded in the sediment deposited in the 2015 flood in our study area. In contrast, and TN levels between 0.07% and 0.27% of TN were recorded for the lower Orinoco (Dezzeo et al. 2000).

The variable deposition of sediments, P, and N detected in our results has formerly been identified in other fluvial systems (Dezzeo et al. 2000; Steiger & Gurnell 2002). During the two autumn-winter floods (2014-2015), the deposition of both P and N was fairly consistent, even among different forest types. On the other hand, during the summer flood (2016) quantities of both nutrients were markedly higher and levels varied substantially among the three forests. The sediment types in the Bermejo River, which is a tributary of the Lower Paraná River, have proved to be positively correlated with the concentrations of calcium and phosphorus in that section of the Paraná (De Cabo & Seoane 2005). This could explain the variation of P in the summer flood, since the Paraná River receives the wash load coming from the Bermejo River mostly between December-April, (Amsler et al. 2007).

The differences in P and N concentration also could be associated with the sediment texture, although there is no current consensus about that relationship. For instance, it has been pointed out that the texture of the sediments plays an important role in controlling the distribution of P, N, and C – i.e., sediments dominated by finer fractions present higher concentrations of P, N and C (Pinay et al. 1992)-. However, a study by Dezzeo et al. (2000) showed no relationship between concentrations of N and the sand or clay content. In another study, no significant relationship between the concentration of P and sediment texture was detected, although a significant positive relationship was found between the concentration of N and the percentage of silt plus clay (Steiger & Gurnell 2002). Thus, it has been proposed that the quantity of P deposited is strongly related to the *quantity* of sediment deposited, but quantities of N may be determined by both *quantity and texture* of deposited sediment (Steiger & Gurnell 2002). Also, for the concentration of P, it has been pointed out that the capacity of sediments to adsorb and retain phosphate is strongly influenced by their mineral composition (Dezzeo et al. 2000), a more specific factor of sediment structure than texture.

5. CONCLUSIONS

Our results provide evidence that autumn-winter floods of the Paraná fluvial system can be as important as the summer floods in terms of sediment and nutrient deposition. We also found that the structural and floristic attributes of riparian forests, as well as their elevation, flow resistance and geomorphologic context, have a great impact on the amount and texture of the deposited sediments. Furthermore, the levels of TP and TN deposited with sediments are comparable to or even higher than those in the fertilized upland soils. Although we have only considered one replica of the three types of forests -among the most representative forests of the Paraná River fluvial system-, these results provide evidence that due to the temporal unbalance in the income of the liquid and solid discharge, autumn-winter floods are very important to sediment and nutrient deposition, and also illustrate the role of floods as natural agents of fertilization for floodplain-river ecosystems.

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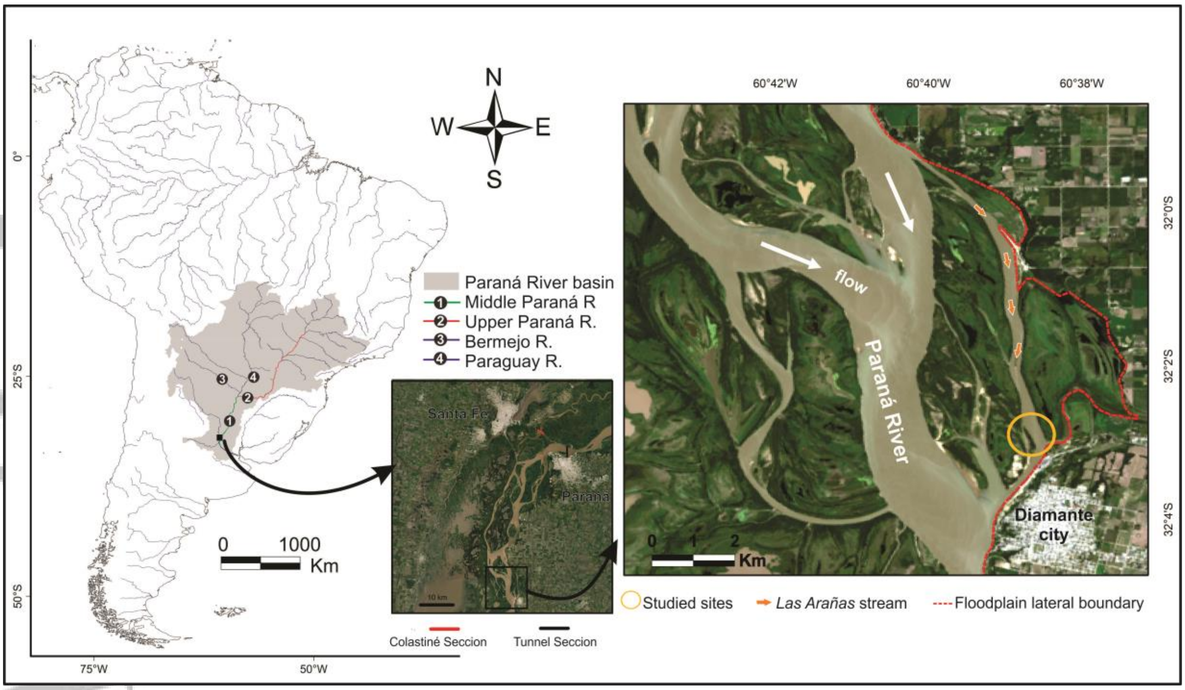


Figure 1: The study area in the context of the Paraná River and its basin.

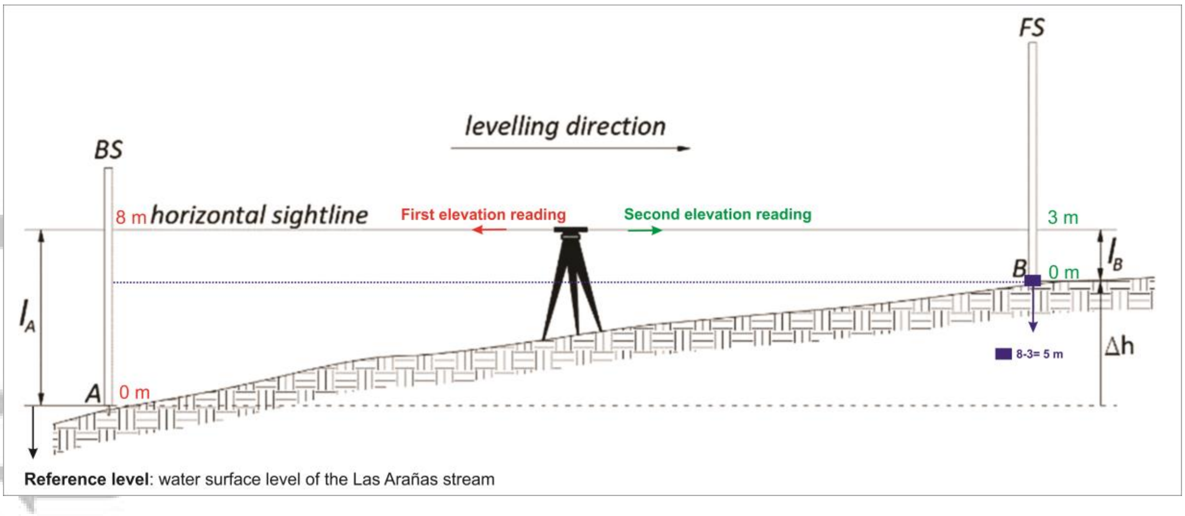


Figure 2: Geometric levelling procedure follow to measure the elevation of forests. Modified from Zrinjski et al. 2018

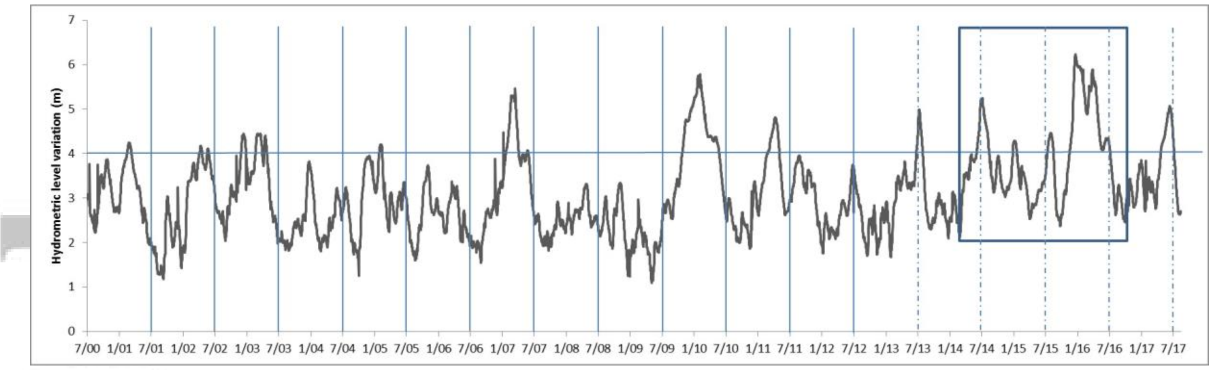


Figure 3: Long-term hydrometric level fluctuations of the Paraná River at Paraná gauge station. Black box indicates the studied floods (winter and summer ones). Vertical lines highlight austral winters (dotted lines refer especifically to winters when floods occured).

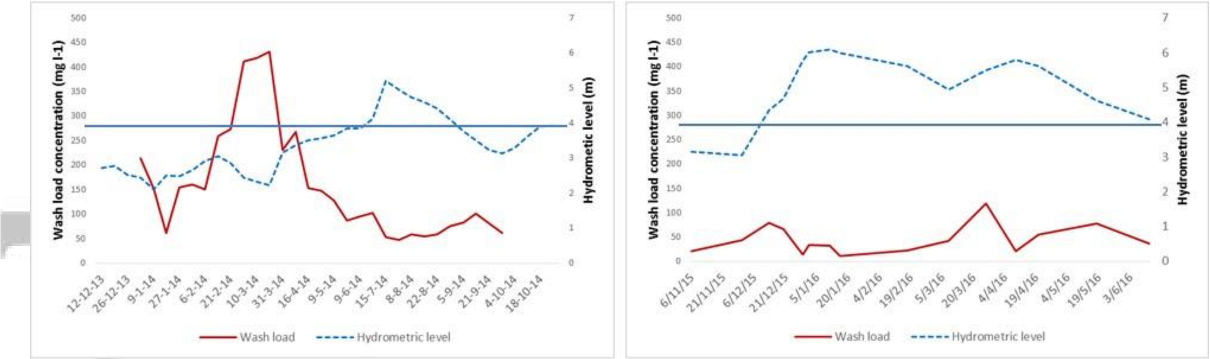


Figure 4: Temporal evolution of wash load concentration and hydrometric level of the Paraná River at Paraná gauge station, for winter (2014) and summer (2016) floods. The horizontal full line indicates a general overflow level for the whole floodplain.

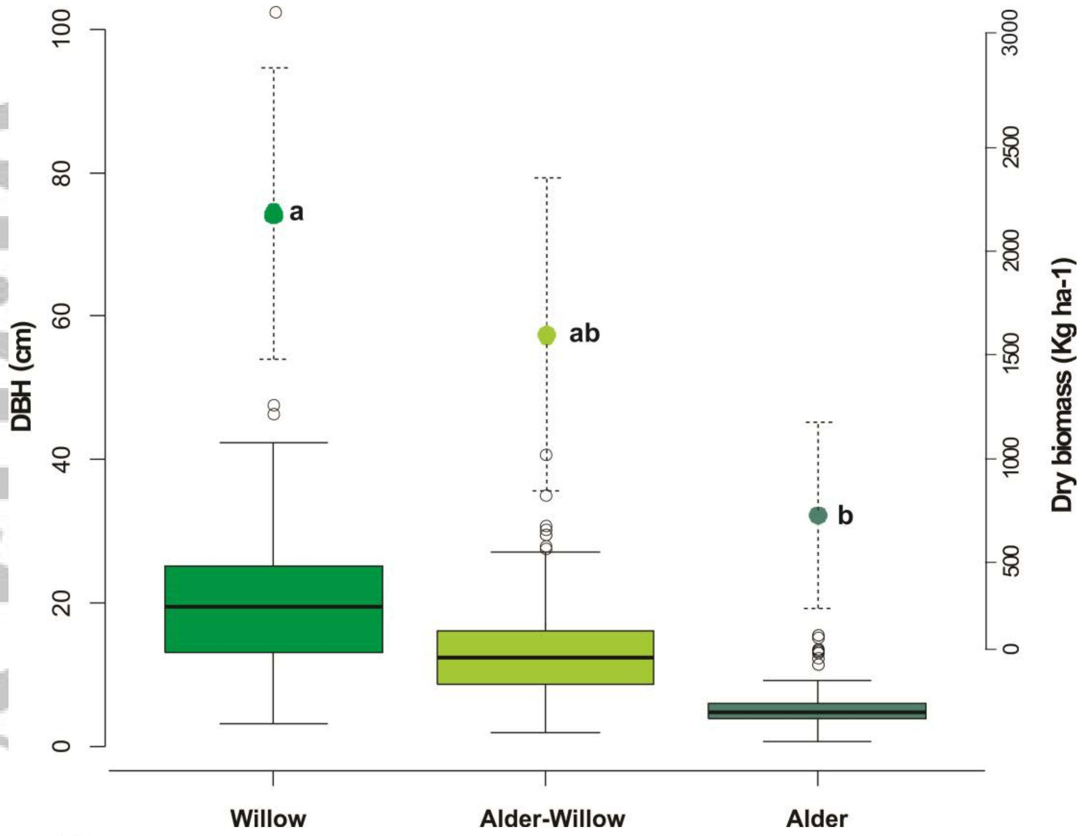
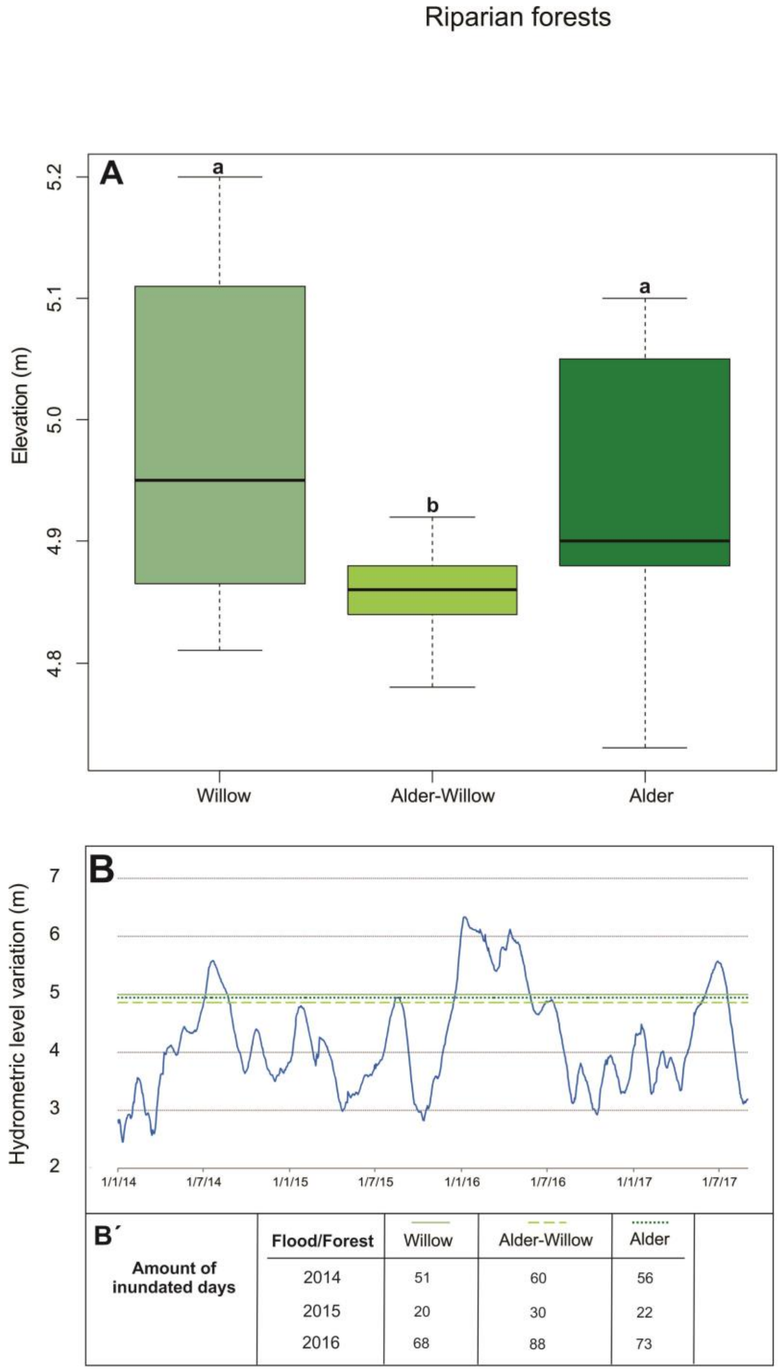


Figure 5. Diameter at breast height (DBH) and dry herbaceous biomass on the left (box-plots) and right (points) axis, respectively. Letters show that willow and alder forests were significantly different at $p \leq 0.05$ in dry biomass.



Amount of inundated days

Flood/Forest	Willow	Alder-Willow	Alder
2014	51	60	56
2015	20	30	22
2016	68	88	73

Figure 6. A-Elevation of riparian forests, different letters indicate statistical differences at $p \leq 0.05$. **B.** Hydrometric level variation of the Paraná River in Diamante (the closest gauge station to the study sites) and mean elevation of forests indicated by the different green lines. **B´.** Ammount of inundate days is presented for each flood and forests according with their mean elevation.

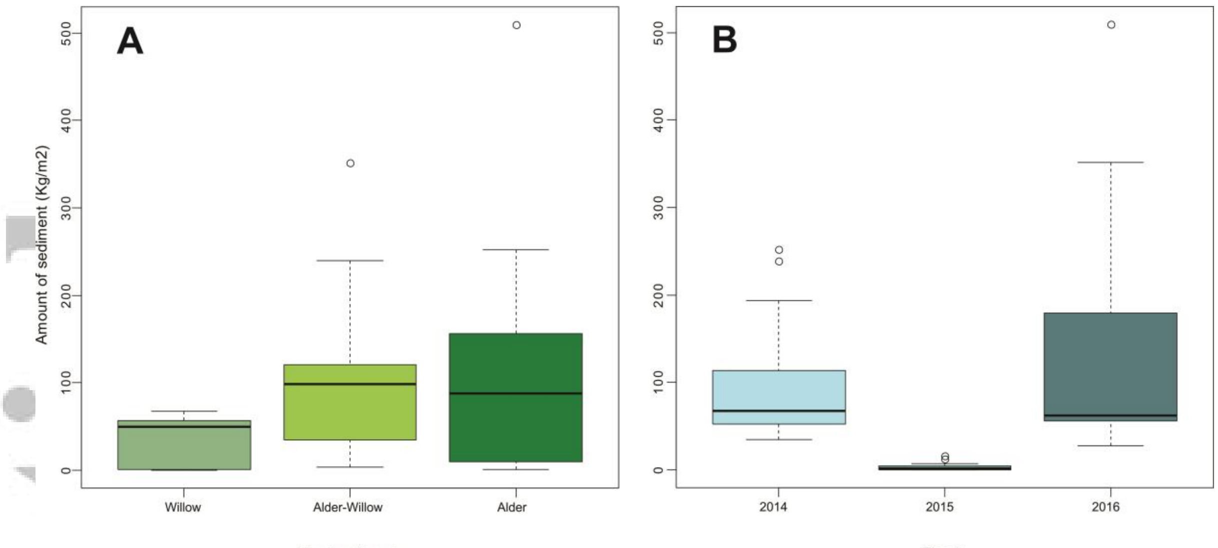


Figure 7. Dry weight of sediment deposited in riparian forest (A) and flood events (B).

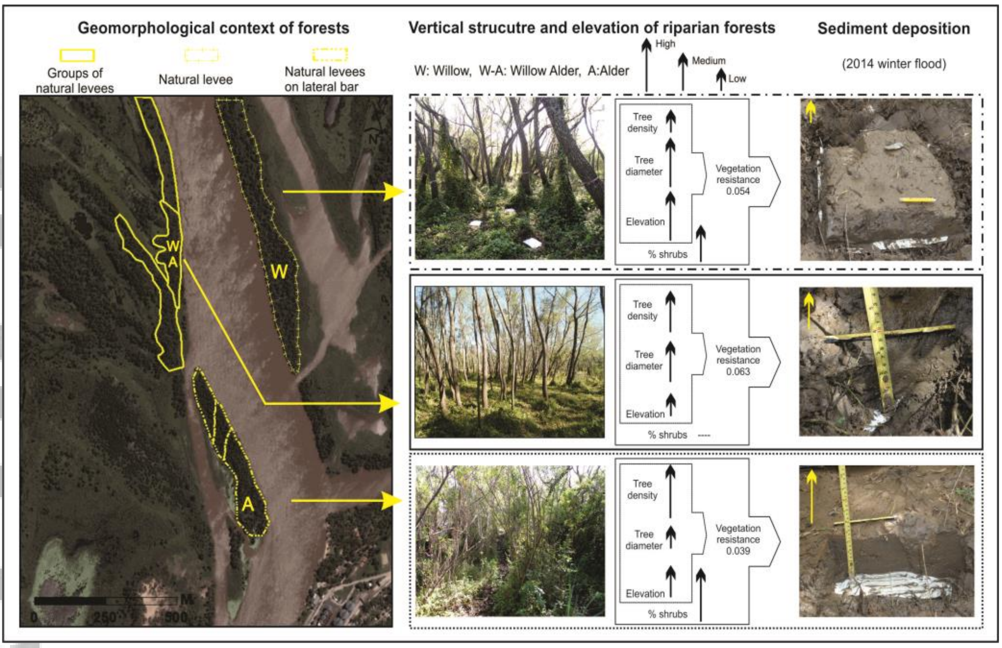


Figure 8- Geomorphological context of sedimentation proccesses, vertical strucutre of riparian forest and sediment deposition during 2014 flood.

Table I. Characteristics of the three flood events for which sediment and nutrient deposition were measured. Discharges were calculated from data reported for the Tunnel Subfluvial and Colastiné Sections. An overflow level of four meters was considered when analyzing flood duration

FLOOD CHARACTERISTICS	**FLOODS**		
	2014	**2015**	**2016**
Austral Season	Winter	Winter	Sumer
Start date	21/6/2014	29/7/2015	3/12/2015
End date	1/9/2014	3/9/2015	24/7/2016
Duration (days)	73	37	233
Max. water level reached	5.24	4.46	6.23
Max. and Mean water level above bankfull stage	1.24-0.68	0.46-0.30	2.23-0.68
Mean discharge (m^3/s^{-1})	21,744	20,187	23,819
Max. discharge (m^3/s^{-1})	23,985	20,760	32,189
Drained water volume (Hm^3)	137,143	64,532	484,622
Max. and Min. wash load concentration (mg l^{-1})	103-47	—	118-11
Total wash load (Tn)	9,720,529	—	20,648,698

Table II. Main characteristics of the studied riparian forests

ESTRUCTURAL AND FLORISTIC FEATURES		**FORESTS**		
		Willow	**Alder-Willow**	**Alder**
Total number of species (woody-herbaceous)		48 (65% -35%)	34 (65%- 35%)	32 (63%- 37%)
Arboreal stratum	**Density (tres ha^{-1})**	2575	4550	7957
	DBH (cm)	21 ± 12.2 ^{a}	13.8 ± 6.5 ^{b}	5.3 ± 2.8 ^{c}
	Resistance of vegetation to flow	0.054	0.063	0.039
	Dominant species	*Salix humboldtiana*	*Tessaria integrifolia* *S.humboldtiana*	*T. integrifolia*
Shrub stratum	**Soil coverage (%)**	30	0	75
	Dominant species	*Baccharis salicifolia,* *Solanum amygdalifolium,* *Byttneria filipes*	0	*B. salicifolia*
Herbaceous/ sub-shrub stratum	**Dry biomass (KgMS ha^{-1})**	2181^{a}	1598^{ab}	726^{b}
	Dominant species	*Teucrium vesicarium,* *Lippia alba,* *Phyla nodiflora* var. *reptans*	*Cynodon dactylon,* *Xanthium cavanillesii*	*Ludwigia peploides,* *Eichhornia crassipes*

Table III Main characteristic of the sediments and nutrients deposited in the different types of floods and riparian forests

FLOOD / FORESTS	**FLOODED DAYS**	**SEDIMENT CHARACTERISTICS**								
		Amount (kg m^{-2})		**Average Daily Rate**	**Texture and Particle size (%)**				**Nutrient (kg ha^{-1})**	
2014		Mean ± SD	Range	(kg m^{-2}day^{-1})	Texture	Clay	Silt	Sand	PT	NT
Willow	**51**	55 ± 6.4	47-68	1.07 ± 0.125	Loam silt	18 ± 1.4	69 ± 1.3	13 ± 2.2	213 ± 4.2	163 ± 11.7
Alder-willow	**60**	97 ± 43.1	35-193	1.61 ± 0.71	Loam silt	12 ± 1.3	54 ± 3.7	34 ± 4.5	264.2 ± 3	267.3 ± 46.4
Alder	**56**	164 ± 63.9	87-252	2.92 ± 1.14	Silt	11 ± 1.9	48 ± 10.6	41 ± 12.2	264.2 ± 3	267.3 ± 46.4
2015										
Willow	**20**	0.2 ± 0.5	0-1	0.01 ± 0.025	Loam silt	20	64	16	1	4.2
Alder-willow	**30**	4 ± 0.5	4-5	0.13 ± 0.016	Loam silt	24 ± 1	66 ± 1.4	10 ± 1.9	17.01 ± 0.9	50.52 ± 75.2
Alder	**22**	7 ± 5.7	2-17	0.31 ± 0.25	Loam silt	19 ± 5.7	60 ± 10	21 ± 14	19.03 ± 0.5	36.72 ± 13.2
2016										
Willow	**68**	53 ± 13.7	28-68	0.77 ± 0.2	Loam silty clay	29 ± 3.6	66 ± 3.1	5 ± 4.4	323.6 ± 17.7	280.8 ± 28.1
Alder-willow	**88**	295 ± 55.8	240-351	3.35 ± 0.63	Silt	19 ± 1.6	50 ± 5.1	31 ± 6.5	3070 ± 6.7	1152 ± 7.8
Alder	**73**	228 ± 201.1	56-510	3.12 ± 2.75	Silt	15 ± 1	39 ± 6.8	47 ± 7.7	4919 ± 351.6	626 ± 14.2